

Life Supp & Biosph Sci, Vol. 1, pp. 129-140 © Cognizant Comm. Corp. 1995, Printed in the USA

1069-9422/95 \$5.00 + .00

INCINERATION AS A METHOD FOR RESOURCE RECOVERY FROM INEDIBLE BIOMASS IN A CONTROLLED ECOLOGICAL LIFE SUPPORT SYSTEM

DAVID L. BUBENHEIM, Ph.D* and KANAPATHIPILLAI WIGNARAJAH, Ph.D.†

NASA Ames Research Center, Advanced Life Support Division,
Regenerative Systems Branch, Moffett Field, CA

Resource recovery from waste streams in a space habitat is essential to minimize the resupply burden and achieve self-sufficiency. In a Controlled Ecological Life Support System (CELSS) human wastes and inedible biomass will represent significant sources of secondary raw materials necessary for support of crop plant production (carbon, water, and inorganic plant nutrients). Incineration, pyrolysis, and water extraction have been investigated as candidate processes for recovery of these important resources from inedible biomass in a CELSS. During incineration CO_2 is produced by oxidation of the organic components and this product can be directly utilized by plants. Water is concomitantly produced, requiring only a phase change for recovery. Recovery of inorganics is more difficult, requiring solubilization of the incinerator ash. The process of incineration followed by water solubilization of ash resulted in loss of 35% of the inorganics originally present in the biomass. Losses were attributed to volatilization (8%) and non-water-soluble ash (27%). All of the ash remaining following incineration could be solubilized with acid, with losses resulting from volatilization only. The recovery for individual elements varied. Elemental retention in the ash ranged from 100% of that present in the biomass for Ca, P, Mg, Na, and Si to 10% for Zn. The greatest water solubility was observed for potassium with recovery of approximately 77% of that present in the straw. Potassium represented 80% of the inorganic constituents in the wheat straw, and because of slightly greater solubility made up 86% of the water-soluble ash. Following incineration of inedible biomass from wheat, 65% of the inorganics originally present in the straw were recovered by water solubilization and 92% recovered by acid solubilization. Recovery of resources is more complex for pyrolysis and water extraction. Recovery of carbon, a resource of greater mass than the inorganic component of biomass, is more difficult following pyrolysis and water extraction of biomass. In both cases, additional processors would be required to provide products equivalent to those resulting from incineration alone. The carbon, water, and inorganic resources of inedible biomass are effectively separated and output in usable forms through incineration.

Incineration	Inedible biomass	Resource recovery	Waste streams
Controlled Ecological Life Support System (CELSS)			

*Address correspondence to David L. Bubenheim, Ph.D., NASA Ames Research Center, MS 239-15, Moffett Field, CA 94035.

†The Bionetics Corporation at NASA Ames Research Center.

INTRODUCTION

The NASA Controlled Ecological Life Support System (CELSS) program was initiated to provide self-sufficiency and safety for humans during long-term missions in space. Self-sufficiency dictates that the greatest practical level of mass recycle be achieved. This task requires the production of food, air, and water of appropriate quality and quantity to support humans through the recycle of resources recovered from waste streams. Green plants are key in such a system, as they represent the only potential for food production while at the same time producing oxygen and water and removing CO₂ from the atmosphere. In a CELSS, human products and inedible biomass will represent significant sources of secondary raw materials necessary for support of crop production (carbon, water, and inorganic plant nutrients). The likely quality and generation rates of secondary raw materials to be expected in a crewed space habitat are summarized in Table 1 (Golub and Wydeven, 1992; Wydeven and Golub, 1991).

Water is a component of every waste stream and represents the largest single resource mass, comprising 93% of total mass (Golub and Wydeven, 1992; Wydeven and Golub, 1991; Wydeven et al., 1989). The dry mass of streams potentially providing CO₂ and inorganic nutrients (toilet waste, inedible biomass, and food preparation waste) generated each day is less than 1 kg per person. Inedible biomass has been estimated to be the dominant resource (Golub and Wydeven,

1992; Wydeven and Golub, 1991) with a dry composition of approximately 43% oxygen, 43% carbon, 6% hydrogen, and 8% other inorganic elements (Salisbury and Ross, 1985). Several physical, chemical, and biological waste treatment processes have been considered for use as the primary processor in a resource recovery system for CELSS (Bubenheim, 1991; Jagow, 1972; Johnson and Wydeven, 1985; Oakley et al., 1989; Wydeven, 1988). These technologies have been reviewed several times in the past few years (Wydeven et al., 1989; Wydeven, 1988; Bubenheim and Wydeven, 1994). Research into resource recovery from solid, secondary raw materials such as inedible biomass has emphasized development of physical/chemical processors. The speed with which wastes can be oxidized by physical/chemical oxidation and the resulting purity of separated output streams (CO₂, H₂O, and inorganics) makes these technologies very desirable. Recovery of inorganic plant nutrients is considered a function of the resource recovery system.

However, the ability of most candidate processors to provide inorganic nutrients in an appropriate form for crop production is not well defined.

The primary candidates for treatment of inedible biomass are the thermal oxidation processes of super-critical water oxidation (SCWO), wet oxidation, and incineration. Thermal/chemical degradation of biomass through pyrolysis is of interest, especially given the recent development of commercial hardware (Suzuki et al., 1990). In pyrolysis the thermal/chemical decomposition occurs in the absence of oxygen and results in the production of volatile gases and nonvolatile char and ash. In toxic waste treatment, a second step is added to pyrolysis where the volatiles are oxidized by incineration. However, some carbon remains in the char that is not in a usable form, at least not in support of plant growth.

Both incineration and SCWO offer the potential of a single-step oxidation process that provides high-quality waste-derived products. In the case of incineration, carbon from the organic waste components is converted to CO₂, a desirable and easily

Table 1. Primary Waste Streams and Estimated Generation Rates in a CELSS

Waste Stream	Mass Generated kg person ⁻¹ d ⁻¹
Hygiene water	23.4
Toilet waste	2.7
Inedible biomass	6.4
Humidity condensate	2.4
Food preparation waste	0.1
Trash	0.9

Source of data: Golub and Wydeven (1992), Wydeven and Golub (1991), and Wydeven et al. (1989).

recovered product. Water is evaporated and can be condensed from the exhaust gas stream, and the inorganics are separated as a low mass ash. SCWO has many of the same features and has been the subject of recent CELSS resource recovery research (Bramlette et al., 1990). Application of SCWO is still limited by several significant obstacles in the engineering of operational systems and lack of a clear understanding of how to control the process to produce the desired products.

Incinerators are operational around the world and are used to process toxic wastes as well as typical domestic community wastes. Given the advanced level of hardware and experience with incineration in solid waste processing, it is appropriate to explore the potential application of this technology in a CELSS (Labak, Remus, and Shapira, 1972; Upadhye, Wignarajah, and Wydevan, 1993). We decided to investigate the ability to recover secondary raw materials from inedible biomass through the thermal oxidation process of incineration. The emphasis of this article is on recovery of inorganics for the purpose of supplying nutrients for utilization in the hydroponic crop growth system of a CELSS.

In this article we attempt to characterize the inorganic mass balance associated with incineration of inedible biomass from wheat. We also attempt to define the efficiency of inorganic recovery provided by incineration followed by water solubilization of the ash. Comparisons of recovery efficiencies are made among incineration, pyrolysis, water extraction of biomass, and water and acid solubilization of ash.

MATERIALS AND METHODS

Biomass

Wheat straw was used as the inedible biomass source. The wheat was grown in controlled environment production chambers at Ames Research Center. The environmental conditions were maintained at a temperature of 22°C, 24-h photoperiod, 1200 $\mu\text{mol m}^{-2} \text{s}^{-1}$ photosynthetic photon flux, and CO_2 concentration of 1200 $\mu\text{mol mol}^{-1}$.

The nutrient solution composition is listed in Table 2.

Wheat was grown to maturity and harvested. Seed heads were separated from stems, leaves, and roots. The stem and leaves were combined, dried at 70°C in a draught oven, ground to pass through a 40 mesh screen using a Wiley mill, and thoroughly mixed to ensure homogeneity of the sample. A portion of the leaves and stem tissue remained unground to be used in particle size studies. Inorganic content of the biomass was characterized using inductive coupled plasma (ICP), ion chromatography (IC), and thermal arc spectroscopy analyses.

Thermal Gravimetric Analysis (TGA)

Ground wheat samples were subjected to thermal gravimetric analysis in an atmosphere of air to mimic incineration, and in the presence of nitrogen to mimic pyrolysis. A linear heating rate of 10°C min⁻¹ was used in all cases. The end-point temperature reached in air was 600°C, whereas in nitrogen the heating was continued to 1100°C. The analysis was carried out on a DuPont differential thermal analyzer with 15-mg samples of the inedible biomass.

Table 2. Elemental Composition of Hydroponic Nutrient Solution Used in Production of Wheat in Controlled Environment Production

Element	Solution Concentration ($\mu\text{mol kg}^{-1}$)
N	14400
P	1000
K	4000
Ca	1250
Mg	650
Na	150
Zn	2.5
Cu	0.75
Fe	10
Mn	5
B	20
Mo	0.25
Si	75

Incineration Conditions

A laboratory muffle furnace was used to perform the incineration. Ceramic crucibles were used to hold 4 g of ground biomass for incineration. Temperature of the samples was maintained at 1000°C. This temperature has been recommended by Upadhye et al. (1993) primarily to avoid the production of dioxins, which are reported as products of combustion at temperatures lower than 750°C. Temperature was maintained for specified periods of time ranging from 1 to 4 h and the majority of the data is presented for a 1-h incineration period. For each treatment a minimum of five replicate samples were incinerated.

Water Extraction of Biomass and Incinerated Ash

Water extraction was utilized as the method to recover water-soluble inorganics from ground biomass and from incinerated biomass ash. The solid samples, 100 mg of ground biomass and approximately 250 mg of ash, were placed in centrifuge tubes, 50 ml of boiling water added, shaken for 30 min, and then centrifuged at $2500 \times g$ for 1 min to separate solid and liquid phases. The inorganic content of the liquid was analyzed using IC and ICP and total organic carbon (TOC) determined; solid samples were analyzed using thermal arc spectroscopy.

Acid Extraction

Acid extractions were performed on ground biomass, ash following incineration, and the non-water-soluble fraction of the incinerated ash. Samples were dissolved in 1.5 M (10%) nitric acid, which extracts all the inorganic elements (Bradford et al., 1976) and the resulting solution was characterized using IC and ICP.

Treatment Replication and Statistical Analysis

Analytical results were determined for a minimum of five replicate samples for each treatment. In the case of incineration, three replicate samples (separate crucibles) were included during each of the five runs of the incinerator. Differences among the three samples in any run of the inciner-

ator were extremely small; the differences among runs of the incinerator are included in the results. Means, standard errors, and standard deviation were calculated for each treatment. In most cases, 1 standard deviation was less than 1.5% of the mean value and in no case was the standard deviation greater than 2.5%. Calculated percentages are reported for the most part in the article.

RESULTS AND DISCUSSION

Thermal Gravimetric Analysis During Incineration and Pyrolysis of Biomass

Plant tissue is primarily composed of polysaccharides (such as cellulose and hemicellulose), proteins, phenolic compounds (such as lignin), oils, inorganics, and water. During incineration (thermal decomposition in the presence of air) of the inedible biomass of wheat, the decomposition and oxidation of many of these components can be identified in the TGA curve (Fig. 1). The initial small decline in mass with initiation of increasing temperature is associated with water loss. A 78% mass loss occurs sharply at 200°C and plateaus at 295°C, characteristic of cellulose combustion (Tang, 1967; Tang and Neill, 1968). Again, between 400° and 450°C a sharp decline in mass is observed, characteristic of combustion of the large molecular weight components such as lignin. The relative magnitude of the two sharp points of declining mass are approximately proportional to the cellulose/hemicellulose and lignin content of wheat straw. The shallow decline in mass at temperatures greater than 450°C is the likely result of continued thermal decomposition of difficult-to-oxidize compounds. At a temperature of 600°C, approximately 8% of the original mass remained.

If the atmosphere of the TGA apparatus is maintained with nitrogen rather than air, as was the case for incineration, pyrolysis of the sample can be estimated. During pyrolysis it appears that the thermal decomposition of polysaccharides again is characterized by a sharp decline in mass but it is initiated at a temperature approximately 50°C greater than observed in incineration. The mass decline resulting from decomposition of the polysaccharides during pyrolysis is approximately

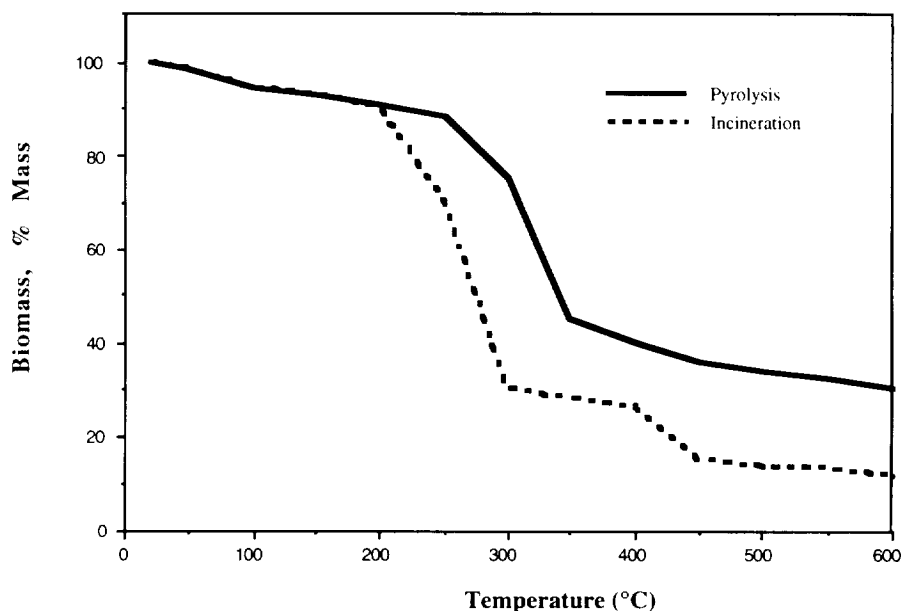


Figure 1. Thermal gravimetric analysis (TGA) of inedible biomass of wheat during incineration and pyrolysis.

75% of that observed during incineration. Further decomposition during pyrolysis is characterized by a shallow decline in mass. As the temperature was increased to 1000°C during pyrolysis (data not shown), the mass had decreased to approximately 15% of the original mass, never reaching the 8% level observed for incineration at 600°C.

Although the gaseous products of incineration and pyrolysis were not analyzed in these studies, CO₂ is a likely product of incineration, containing a significant amount of an important resource, carbon. Because pyrolysis occurs in the absence of oxygen, only minimal oxidation can occur. The likely composition of carbon compounds resulting from pyrolysis could be estimated (Alger, 1972), but CO₂ would not be present in large amounts. Recovery of the carbon as CO₂ would require further incineration of the gaseous products. In this regard, there appear to be several disadvantages of pyrolysis when compared with incineration. A second thermal process is required to oxidize the gaseous carbon, significantly higher temperature is required, and the mass of the remaining ash (char) residue is almost twice that resulting from

incineration. A large percentage of that char resulting from pyrolysis would be carbon.

Biomass Elemental Composition and Retention During Incineration

Analysis of the elemental composition of the inedible wheat biomass showed that inorganics represented 7.5% of the dry mass (Table 3). Approximately 80% of the total inorganic content was potassium.

Following incineration of the biomass samples, the remaining ash was consistently 7% of the original sample mass. If none of the inorganics were lost during incineration and if perfect oxidation was accomplished, we would expect the mass of the remaining ash to be slightly greater than the sum of all inorganics in the original biomass, as the oxidized products would have gained the mass of the oxygen.

Although the degree of oxidation was not fully determined, organic carbon was completely lost during incineration. Approximately 8% of the total biomass was carbon present as soluble organic

Table 3. Element Composition of Hydroponic Nutrient Solution Used in Production of Wheat in Controlled Environment Production

Element	Elemental Composition (mg kg ⁻¹ Dry Mass)	Elemental Retention in Incinerator Ash (% Biomass Content)
K	6.1 ± 0.185*	90
Ca	1.0 ± 0.019	100
P	0.21 ± 0.0024	100
Mg	0.13 ± 0.0008	100
Na	0.01 ± 0.0002	100
Fe	0.01 ± 0.0001	35
Mn	0.004 ± 0.0001	100
Zn	0.003 ± 0.0005	10
Cu	0.0008 ± 0.00004	55
Si	0.04 ± 0.001	100
Total inorganic	7.5	91
Total organic carbon	8.1	0

*Standard errors; $n = 5$.

carbon. The 35% of total biomass making up the remainder of the carbon balance was in other forms, such as cellulose.

Loss of potential resources resulting from the process of incineration was quantified by determining the retention of inorganics in the ash compared with the original biomass content.

The retention of the larger mass fraction components of the biomass (K, Ca, Mg, and P) is high, resulting in an overall retention for inorganics of 92%. Some of the inorganics are clearly lost during incineration at 1000°C, probably through volatilization. Retention of several of the elements in the ash was very low; zinc retention was only 10% of that present in the biomass. Potassium, which is abundant in biomass, is known to be subject to volatilization during biomass combustion (Humphries, 1956). Elemental analysis procedures for plant material dictate that temperatures must remain below 480°C to retain all potassium. Our results indicate that longer exposure periods at a temperature of 1000°C also result in increasing potassium volatilization.

Incineration Duration and Elemental Retention

The inorganic content of incinerator ash decreased with increasing processing time at 1000°C.

Following 1 h of incineration, 91% of the inorganic mass of the original biomass was measured in the ash, with this percentage decreasing to 87% after 4 h (Fig. 2). Although the total amount of inorganics decreased, not all elements responded in the same manner. Calcium and magnesium content in the ash actually increased with increased incineration time. Calcium increased from 45% to 70% and magnesium from 57% to 86% of that measured in the original biomass, with 1- and 4-h incineration periods. Reaction with the ceramic crucible was originally thought to have caused the decrease in Ca, Mg, and Fe. However, acid rinsing of crucibles has not resulted in recovery. We continue to pursue an explanation. Potassium in the ash decreased as expected from 90% after 1 h to 74% after 4 h at 1000°C. Phosphorus decreased only slightly with incineration time, from near 100% at 1 h to 93% after 4 h. Potassium represents such a large fraction of the total inorganic content of the biomass that volatilization of this element dominates the total inorganic mass trend. Careful control of the incineration process is required to attain efficient recovery of potassium. If incineration temperature was inadvertently allowed to rise above 1000°C, potassium retention could be decreased to less than 50%. The challenge for design of an effective incinerator for inorganic recovery, and possibly the "acid test" for such a design, will be the degree of potassium retention.

Biomass Particle Size and Elemental Retention During Incineration

Particle size of the biomass being incinerated had a large influence on the amount of inorganic retained in the ash. Elemental retention following 1- and 4-h incineration was recorded for wheat stem samples ground to pass through a 40 mesh screen compared with that following incineration of stem pieces cut to 2-cm lengths. The retention of all elements was significantly greater with smaller particle size, but only potassium is discussed here as an example of trends. Potassium retention was 90% with 1-h incineration of ground samples and only 30% with the larger stem pieces.

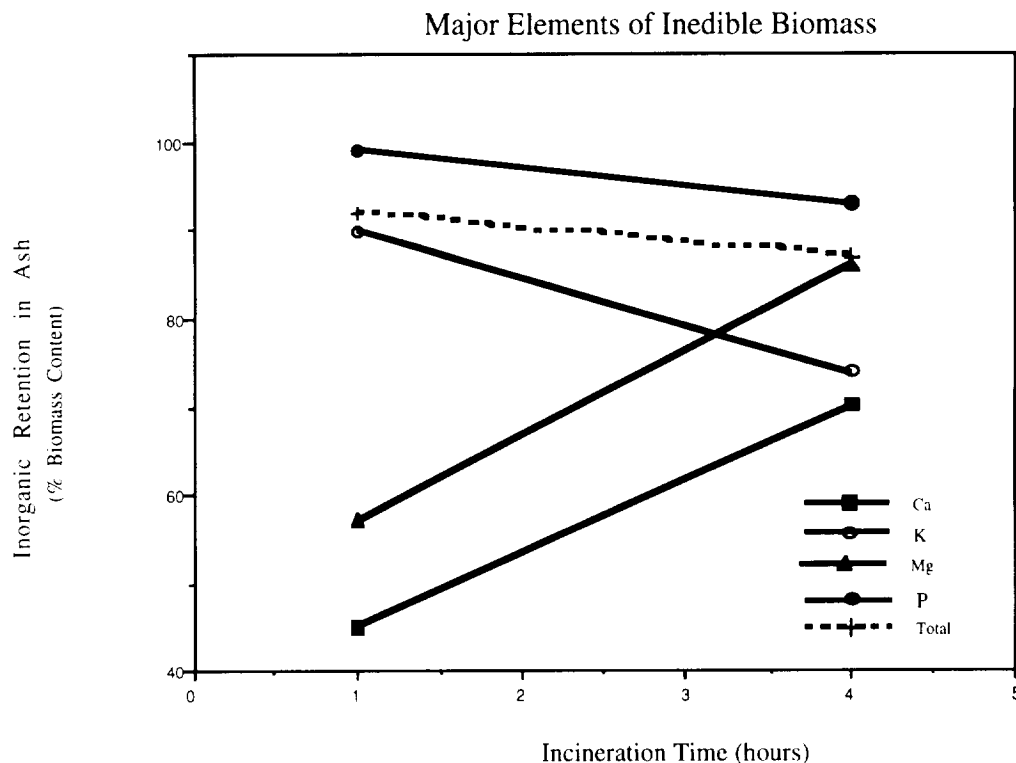


Figure 2. Influence of incineration period on elemental retention.

When ground samples were incinerated for 4 h, retention decreased to approximately 75%; however, in the case of the stem pieces, potassium retention increased slightly with incineration time, but only reached 35%.

Water Solubility of Incinerated Biomass Ash and Elemental Recovery

Water extraction appears to be an effective method of recovery for some inorganic elements from incinerated biomass (Table 4). Approximately 72% of the inorganic mass in the ash was water soluble. The resulting overall recovery efficiency of inorganics from biomass was 65%. That is, 65% of the inorganic mass originally measured in the inedible biomass was recovered in the water-soluble fraction of incinerated ash. Potassium in the ash appears to be present in predominately water-soluble forms because 86% of the potas-

Table 4. Solubility of Inorganic Elements Retained in Incinerated Biomass Ash Using Water as the Solvent and the Resulting Recovery Efficiency for These Elements From Inedible Biomass

Element	Water-Soluble Fraction of Ash (%)	Recovery Efficiency From Inedible Biomass* (% of Biomass Content)
K	86.0	77.4
Ca	0.2	0.2
P	36.0	35.6
Mg	0.6	0.6
Na	93.0	2.1
Fe	0.4	0.1
Mn	1.0	1.0
Zn	21.0	2.1
Cu	4.0	2.2
Si	0	0
Inorganic recovery	72.4	65.2

*Recovery efficiency is defined as the percentage of inorganic elements present in biomass that are finally partitioned into the water-soluble fraction of incinerated ash. This efficiency is calculated for each element and for the total inorganic component of the biomass.

sium in the ash was soluble, leading to a 77% recovery of potassium from the original biomass. Sodium was the only other element clearly present in water-soluble forms in the ash (93% solubility). This high solubility and effectively total retention during incineration led to high total recovery for sodium. Although calcium and magnesium retention was high during incineration, they are present in the ash in non-water-soluble forms. Less than 1% of these elements could be dissolved in water following incineration. Phosphorus and zinc exhibited moderate to low solubility of 36% and 21%, respectively.

As a result of differences in retention during incineration and solubility in water, the relative proportions of inorganics in the biomass is not reflected in the recovered elements. Because of the recalcitrant forms of most elements in the ash, potassium was the predominant element recovered in the water-soluble fraction of ash. Potassium made up 87% of the water-soluble fraction whereas it represented 80% of the biomass inorganic content.

The compounds formed during incineration of the biomass and present in the ash have not been identified at the time of writing this article. We can postulate, however, based on the solubility exhibited for these elements, that silicates and oxides are formed. There is further evidence that phosphates and sulfates are also formed, and another likely companion would be sulfides.

Water Solubility of Inedible Biomass and Elemental Recovery

An alternative approach to inorganic recovery is extraction from biomass prior to oxidation (Upadhye et al., 1993; Garland and Mackowiak, 1990). Previously, Garland and Mackowiak (1990) reported approximately 60% inorganic recovery by soaking dried wheat straw in 23°C water for 4 days and collecting the water-soluble fraction. Given the similarity to the recovery efficiency described above for incineration followed by water extraction, we decided to determine the water solubility of inorganics from the same biomass that was used in the incineration trials. The same water

extraction process used for incinerated ash was employed and 50 ml of boiling water was added to a centrifuge tube containing 100 mg of ground sample. The tube was shaken for 30 min and then centrifuged to separate the liquid from the solid residue. All elements, except sodium, were more water soluble from the dried biomass than from the incinerated ash (Table 5). The overall inorganic recovery from this method was 93%. This recovery was significantly greater than the 60% reported by Garland and Mackowiak (1990). Although the elemental composition of the wheat used in this study was very similar to that used by Garland and Mackowiak, we decided to use the individual element recovery efficiencies reported by them to calculate what the recovery would be from our sample because there were some differences in tissue contents for the lower mass elements (Table 5). These differences in composition led to an estimation of 73% recovery from our sample rather than the 60% previously reported;

Table 5. Elemental Recovery Using Water Extraction of Biomass

Element	Short-Term Extraction Hot Water/ Ground Tissue (% of Biomass Content)	Long-Term Extraction Warm Water/ Intact Straw (% of Biomass Content)
K	100	78.3
Ca	66.7	50.6
P	81.3	58.0
Mg	100	70.3
Na	31.9	—
Fe	36.2	54.3
Mn	100	34.0
Zn	100	61.5
Cu	41.9	27.3
Dry biomass fraction	7.0	5.5*
Total inorganic recovery	93.2	73.4*

Short-term, hot-water extraction of ground tissue is compared with calculated extraction using long-term soaking of intact wheat straw in warm water. Calculations are based on recovery reported for individual elements by Garland and Mackowiak (1990) and applied to the inorganic content of the biomass under study in this article.

*Dry biomass fraction and total recovery efficiency assume 100% of the sodium in the biomass was soluble in the long-term extraction; no recovery efficiency could be calculated for sodium.

however, this estimate was still lower than the recovery we observed from water extraction of our samples. The difference in recovery probably results from greater surface area exposure in the ground tissue, or it could simply be due to the difficulty associated with removing the water from the large straw sample used by Garland and Mackowiak.

In the process of conducting a water extraction of biomass, a large organic fraction is also dissolved along with the inorganics. Garland and Mackowiak approximated this organic fraction to be 40% of the carbon present in the original biomass (Garland and Mackowiak, 1990; Garland, 1992). Thus, approximately 17% of the original biomass was water-soluble carbon, because carbon makes up approximately 43% of biomass. Our results indicated 8% of total biomass was soluble organic, approximately 50% less.

Some treatment of the organic fraction resulting from water extraction of biomass is required prior to delivery to the plants because of potential toxicity and to facilitate full recovery of the carbon. Upadhye et al. (1993) did not recognize the toxic potential but did suggest that a separate oxidizer would be required to recover the carbon from this solution. They also included an incinerator for oxidation of the non-water-soluble residue from the straw. The consequence of incorporating two oxidizers, for liquid and solid waste streams, into a resource recovery system for CELSS will be weighed against the difference in recovery efficiency.

Comparison of Incineration and Water Extraction of Nonoxidized Biomass for Resource Recovery

Inorganic recovery was greater using water extraction of biomass than with incineration. Only 7% of the inorganics are lost when using water extraction compared with 35% for incineration followed by water solubilization (Table 6). Our results indicate that 8% of the inorganics originally found in biomass was lost during the process of incineration and the remaining 27% was present in the ash in water-insoluble forms. Although

water extraction seems desirable, when viewing elemental recovery none of the water or carbon resources are recovered. Even if the biomass is not dried prior to extraction, water from some source must be provided. In water extraction of biomass, the inorganic and organic components are not separated but rather each remain present in both the partitioned solid and liquid streams. During incineration, the desirable resources are segregated and separated by phase, which can greatly facilitate recovery. Carbon can be directly recovered as gaseous CO_2 and utilized by plants, water is concomitantly produced as a gas and should require only a phase change condensation step for recovery, and the inorganics are primarily contained in the solid ash. The largest inorganic component of biomass, potassium, is present in the ash in water-soluble forms. When water solubilization of ash is utilized, the insoluble elements must be supplied to the growing plants from some stored source. Fortunately, the water-insoluble elements retained in the ash are the micronutrients and macronutrients required in relatively small amounts with the largest fractions recovered. Acid solubilization of the ash remaining following incineration offers an apparently effective method for recovery of macro- and micronutrients, with the only real loss occurring as a result of volatilization during incineration. In any case where incineration is utilized, the nitrogen contained in biomass will be partitioned to the gaseous exhaust stream. Selection of the proper resource recovery technology and the approach and integration of technologies must be considered with a sense of the overall mission to be served.

SUMMARY AND CONCLUSIONS

Our results indicate that incineration is an effective method for oxidation of inedible biomass and segregation of the inorganic resources to a small mass, easy-to-handle ash. Sixty-five percent of the inorganic mass was recovered in the water-soluble fraction of the ash. Losses were attributed to volatilization (8%) and non-water-soluble ash (27%). If dilute acid was used to solubilize the ash, then the only mass lost was that due to volatilization during incineration.

Table 6. Comparison of Recovery Efficiencies From Incineration Followed by Water Extraction of Ash With Water Extraction of Dry Biomass

	Incineration Water-Soluble Ash	Incineration Acid-Soluble Ash	Water Extraction of Biomass
Inorganic recovery efficiency from biomass	65%	92%	93%
Inorganic lost	35%	8%	7%
Incinerator loss	8%	8%	—
Water insoluble	27%	—	7%
Estimated carbon recovery	100%	100%	0%
Estimated water recovery	100%	100%	0%

Proper preparation of waste streams prior to processing in a resource recovery system will be critical. It is clear from both elemental retention during incineration and elemental recovery in the water-soluble fraction of dry biomass that smaller particle sizes will result in increased recovery efficiencies.

Water extraction of ground biomass provided greater inorganic recovery than incineration followed by water solubilization of the ash. However, the water-soluble fraction from biomass contains a considerable amount of organic as well as inorganic compounds. This organic component represents a potential plant toxin in nutrient solution. Some of the organic carbon substances extracted from plant tissues or extruded by plant tissues can be toxic to growth and germination of other plant species (Rice, 1984; Yu and Matsin, 1994). This soluble organic component is also a secondary raw material, carbon, in a nonaccessible form. Oxidation of this fraction is required to get CO₂ from this liquid stream. A second oxidation processor would be required to recover carbon from the solid straw residue. Acid solubilization of incinerated ash provided a degree of inorganic mass recovery approximately equal to that with water extraction of nonoxidized biomass. However, the inorganic, organic, and water components remain segregated because of the incineration step. The availability of acid in mission scenarios employing a CELSS is not well defined. Acids may be required to perform a range of functions and may be readily available. The presence of water is clearly a given.

Elements such as potassium and phosphorus are obviously being lost during incineration. These elements are likely being volatilized during the process. If nutrient recovery is of primary concern, then shorter incineration times would be desirable. However, because the inorganics represent such a small portion of the total waste stream from which resources must be recovered in a CELSS, the selection of operating condition might be based on recovery of water and carbon. The potential for toxic products such as dioxins, which are reported to result from incineration temperatures lower than 750°C, will add another factor into the calculation.

Elemental recovery following pyrolysis was not investigated in these current studies to the same depth as was incineration. However, it is clear from thermal gravimetric studies that higher processing temperatures are required with pyrolysis to get an equal mass reduction as observed with incineration. Because the temperatures are higher, the potential for volatilization of inorganics is probably greater as well. Further, because the processing occurs in the absence of air (oxygen), an added oxidation step would be required to produce CO₂.

Resource recovery is a critical element in a CELSS. Inorganic plant nutrients in inedible biomass represent a small fraction of the total secondary raw resource pool. However, recycle of these materials is key to accomplishing self-sufficiency. Incineration is an effective processor with potential application in the resource recovery system of a CELSS. All the raw resources resident in bio-

mass are separated and a significant amount of inorganics can be recovered from the water-soluble ash.

ACKNOWLEDGEMENTS

The authors would like to express appreciation to the entire CELSS Research and Technology Development group of the Regenerative Systems Branch at Ames Research Center. We are grateful to Janelle Lee, David Wilson, and Sonja Cronin for technical assistance, Dr. Maynard Bates for constructive discussions and criticisms, Greg Schlick and Catherine Greene for support during crop harvests and other laboratory activities, and Susan Beach for manuscript preparation. We appreciate the quality and timeliness of analysis conducted by Dr. Wade Berry, Leon McAnulty, and Bret Holguin of the Laboratory of Biomedical and Environmental Sciences at UCLA, and the aid of Sal Riccitiello and Meng Da Shu of the Thermal Protection Materials Branch at Ames Research Center. This research was supported by NASA, Controlled Ecological Life Support System Program, RTOP number 199-61-12-28.

Kanapathipillai Wignarajah obtained his Ph.D. in Plant Eco-Physiology in 1974 and was elected a Fellow of the Indian Chemical Society in 1986. His research interests include adaptation of plants to abiotic stress, development of technology for recovery of the resources from plant wastes, and integration of plants in closed life support systems.

David L. Bubenheim obtained his Ph.D. in Crop Physiology in 1986 and is currently Chief Scientist for Research and Technology Development in Controlled Ecological Life Support Systems (CELSS) at NASA's Ames Research Center. His research interests include environmental and ecological plant physiology, closed system dynamics, controlled environment agriculture, technology for resource recovery from wastes, and development of regenerative life support systems.

REFERENCES

- Alger, R. (1972). Pyrolysis and combustion of cellulosic materials. in *Mechanisms of pyrolysis, oxidation and burning of organic materials*. National Bureau of Standards Special Publication 357.
- Bradford, G. R., Page, A. L., Lund, L. J., and Olmstead, W. (1976). Trace element concentrations of sewage treatment plant effluents and sludges: Their interaction with soils and uptake by plants. *J. Environ. Qual.* 4: 123-127.
- Bramlette, T. T., Mills, B. E., Hencken, K. R., Brynildson, M. E., Johnston, S. C., Hruba, J. M., Feemster, H. C., Odegard, B. C., and Modell, M. (1990). Destruction of DOE/DP surrogate wastes with supercritical water oxidation technology. Sandia Report SAND90-8229, Sandia National Laboratories, Albuquerque, NM.
- Bubenheim, D. L. (1991). Plants for water recycling, oxygen regeneration and food production. *Waste Manage. Res.* 9: 435-443.
- Bubenheim, D. L. and Wydeven, T. (1994). Approaches to resource recovery in controlled environment ecological life support systems. *Adv. Space Res.* 14: 113-123.
- Garland, J. L. (1992). Coupling plant growth and waste recycling systems in controlled ecological life support system (CELSS). NASA Technical Memorandum 107544, Kennedy Space Center, FL.
- Garland, J. L. and Mackowiak, C. L. (1990). Utilization of the water soluble fraction of wheat straw as a nutrient source, NASA Technical Memorandum 103497, Kennedy Space Center, FL.
- Golub, M. A. and Wydeven, T. (1992). Waste streams in a crewed space habitat II. *Waste Manage. Res.* 10: 269-280.
- Humphries, E. C. (1956). Mineral components and ash analysis. in *Modern methods of plant analysis*, vol. 1. Editors Paech, K. and Tarcey, M. V. New York: Springer-Verlag.
- Jagow, R. (1972). Development of a wet oxidation waste processing system. Paper 72-ENAV-3, Environmental Control and Life Support Systems Conference, San Francisco, CA. Warrendale, PA: SAE International.
- Johnson, C. C. and Wydeven, T. (1985). Wet oxidation of a spacecraft model waste. SAE Technical Paper 851372, Fifteenth Intersociety Conference on Environmental Systems, San Francisco, CA. Warrendale, PA: SAE International.
- Labak, L. J., Remus, G. A., and Shapira, J. (1972). Dry incineration of wastes for aerospace waste management systems. Paper 72-ENAV-2, Environmental Control and Life Support Systems Conference, San Francisco, CA. Warrendale, PA: SAE International.
- Oakley, D. L., Rosevear, A., Lambe, C. A., and Chipaux, C. (1989). Waste processing. European Space Agency Contract Final Report, Contract 7499/87/NL/MA(SC), Harwell Laboratory, Oxfordshire, OX11 0RA, UK.
- Rice, E. L. (1984). *Allelopathy*. New York: Academic Press.
- Salisbury, F. B. and Ross, C. (1985). *Plant physiology*. Belmont, CA: Wadsworth Publishing Company.
- Suzuki, J., Hosaka, M., Kawasaki, Y., Nishino, A., and Sogen, K. (1990). A microwave burning processor for waste disposal. *J. Microwave Power Electromagnet. Energy* 25: 168-176.

- Tang, W. K. and Neill, W. K. (1968). Effect of flame retardants on pyrolysis and combustion of alpha-cellulose. *J. Polym. Sci. C* 6: 65-81.
- Tang, W. K. (1967). Effect of inorganic salts on pyrolysis of wood, cellulose and lignin determined by differential thermal analysis. USDA Forest Service Research Paper, FLP 82, USDA, Madison, WI.
- Upadhye, R. S., Wignarajah, K., and Wydeven, T. (1993). Incineration for resource recovery in a closed ecological system. *Environ. Int.* 19: 381-392.
- Wydeven, T. (1988). A survey of some regenerative physico-chemical life support technologies. NASA Technical Memorandum 101004, NASA-Ames Research Center, Moffett Field, CA.
- Wydeven, T. and Golub, M. A. (1991). Waste streams in a crewed space habitat. *Waste Manage. Res.* 9: 91-101.
- Wydeven, T., Tremor, J., Koo, C., and Jacquez, R. (1989). Sources and processing of CELSS wastes. *Adv. Space Res.* 9: 85-97.
- Yu, J. Q. and Matsin, Y. (1994). Phytotoxic substances in root exudates of cucumber (*Cucumis sativus*). *J. Chem. Ecol.* 20: 21-31.